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Indian Standard

METHODS OF MEASUREMENTS FOR PROPERTIES OF GYROMAGNETIC MATERIALS FOR USE AT MICROWAVE FREQUENCIES

PART I MAGNETIZATION

UDC 621·318·134·029·6 : 621·317·4

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MANAK BHAVAN, 9 BAHADUR SHAH ZAFAR MARG
NEW DELHI 110002

Price Rs 12·00 Gr 7

January 1978

Indian Standard

METHODS OF MEASUREMENTS FOR PROPERTIES OF GYROMAGNETIC MATERIALS FOR USE AT MICROWAVE FREQUENCIES

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METHODS OF MEASUREMENTS FOR PROPERTIES OF GYROMAGNETIC MATERIALS FOR USE AT MICROWAVE FREQUENCIES

PART I **MAGNETIZATION**

0. FOREWORD

0.1 This Indian Standard (Part I) was adopted by the Indian Standards Institution on 18 May 1977, after the draft finalized by the Magnetic Components and Ferrite Materials Sectional Committee had been approved by the Electronics and Telecommunication Division Council.

0.2 With the increasing use of ferrites in electronics and telecommunication equipment and their availability from indigenous manufacturers, it has become necessary to formulate a series of Indian Standards to establish methods for measuring their properties.

0.3 The object of this series of standards is to establish methods for measuring the properties of gyromagnetic materials for use at microwave frequencies. The methods described herein do not exclude the use of other methods giving substantially the same or better results and accuracy.

0.4 This standard (Part I) is one of the series of Indian Standards relating to methods of measurements for properties of gyromagnetic materials for use of microwave frequencies. A list of standards of this series is given in Appendix A. A list of standards on magnetic components and ferrite materials, so far brought out, is given on page 25.

0.5 In preparing this standard, assistance has been derived from IEC documents 51 (C.O.) 164 and 51 (Sectt) 140 ' Draft measuring methods for properties of gyromagnetic materials intended for application at microwave frequencies ' issued by International Electrotechnical Commission.

0.6 In reporting the result of a test or analysis made in accordance with this standard, if the final value, observed or calculated, is to be rounded off, it shall be done in accordance with IS : 2-1960*.

***Rules for rounding off numerical values (*revised*).**

1. SCOPE

1.1 This standard (Part I) describes method of measurement of saturation magnetization, (M_s) and magnetization (at specified field strength), (M_H) of ferrite materials, for application at microwave frequencies.

> NOTE 1 — For the purpose of this standard, the words 'ferrite' and 'microwave' are used in a broad sense:
>
> a) By 'ferrites' are meant not only magnetodielectric chemical components having a spinel structure, but also materials with garnet and hexagonal structures; and
>
> b) The 'microwave' region is taken to include wavelength between 1 m to 1 mm, roughly, the main interest being concentrated on the region 0·3 m to 10 mm.
>
> NOTE 2 - Examples of components employing microwave ferrites are non-reciprocal devices! such as circulators, isolators and non-reciprocal phase shifters. These constitute the major field of application, but the materials may be used in reciprocal devices as well, for example, modulators and (reciprocal) phase-shifter. Other applications include gyromagnetic filters, limiters and more sophisticated devices, such as parametric amplifiers.

2. DEFINITIONS

2.1 For the definitions of general terms used in this document, reference should be made to IS : 1885 (Part XXXI)-1971*.

SECTION I METHOD FOR MEASUREMENT OF SATURATION MAGNETIZATION, M_s

3. SCOPE

3.1 This section describes the method for measurement of saturation magnetization, M_s, of ferrite materials, for application at microwave frequencies.

4. METHOD OF MEASUREMENT

4.1 Introduction - The saturation magnetization is a characteristic parameter of ferrite materials. It is widely used in theoretical calculations, for example in computation of tensor permeability components. In a variety of microwave applications the saturation magnetization determines the lower frequency limit of the device, mainly due to its importance for the occurrence of so-called low field loss.

4.2 **Object** — Similar alternative techniques for measuring saturation magnetization are covered in this section. These are the vibration coil method (VCM) and vibrating sample method (VSM).

---

*Electrotechnical vocabulary: Part XXXI Magnetism.

4.2.1 The vibrating coil method has the advantages of easier sample mounting and simpler mechanical arrangement when measurements over a range of temperatures are required, particularly at low temperatures.

4.2.2 The vibrating sample method is more accurate given a similar degree of elaboration in electronic equipment.

4.2.3 The apparatus needed in the two cases is very similar and the calibration methods are identical. The same test samples may be used for either technique.

4.3 Theory — When a sphere of isotropic magnetic material is placed in a uniform magnetic field, the sphere becomes uniformly magnetized in the direction parallel to the applied field. The sphere produces its own external magnetic field, equivalent to that of a magnetic dipole at the centre of the sphere and orientated parallel to the direction of magnetization.

If a small detection coil (in practice a pair of coils wound in opposition) is vibrated at small amplitude, close to the sample sphere and in a direction at right angles to the applied field, a voltage E_s will be induced in the coil, proportional to the rate of change of flux φ_s in the coil, due to the sample and at the mean coil position, x_0:

$$E_s = -N \cdot \left(\frac{d\varphi_s}{dx} \right)_{x_0} \frac{dx}{dt} \qquad \text{... (1)}$$

$$\text{or, } E_s = \frac{-GV_s M_s N \omega \delta}{x_0^2} \qquad \text{... (2)}$$

where N is the number of turns on the coil, V_s is the volume of the sample, M_s its saturation magnetization and G is a constant dependent on the experimental configuration.

The motion of the coil, in the X-direction, is given by:

$$X = X_0 + \delta \sin \omega t \qquad \text{... (3)}$$

where X is the displacement at time t, ω is the angular frequency and δ the vibration amplitude.

If the unknown sample is now replaced by a calibrating sample of known saturation magnetization M_c and volume V_c inducing a voltage E_c the magnetization of the sample may be found by comparison:

$$\frac{M_s}{M_c} = \frac{E_s}{E_c} \cdot \frac{V_c}{V_s} \qquad \text{.. (4)}$$

If the induced voltages E_s and E_c give rise to readings E_s' and E_c' from the apparatus, then

$$M_s = M_c \cdot \frac{E_s'}{E_c'} \; \frac{d_c^3}{d_s^3} \qquad \text{... (5)}$$

where d_s and d_c are the diameters of the sample and calibration spheres, respectively.

Identical equations apply in the VSM (vibrating sample method) case, when the sample is vibrated while the coil remains stationary.

4.4 **Test Specimen** -For the dipole assumption to be valid, the test sample should be a sphere, whose deviation from roundness is not more than 0·5 percent. The percentage deviation from roundness is defined as:

$$\frac{(\text{Maximum diameter} - \text{Minimum diameter}) \times 100}{\text{Minimum diameter}} \quad \ldots (6)$$

For most ferrite materials, a diameter of about 2·5 mm is suitable. If it is less than 1 mm, a reasonable signal-to-noise ratio shall be difficult to achieve, particularly when M_s is low. Spheres larger than about 4 mm are less convenient to make and it is not so easy to maintain a uniform applied field over the volume of the sphere.

It may be permissible to use other than spherical samples, provided that the induced voltage may be shown to be a linear function of magnetization to within the accuracy required, and that the calibration sample has identical dimensions to the samples to be measured.

4.5 **Measuring Apparatus for the Vibrating Coil Method (VCM)**

4.5.1 *Arrangement of Detection Coils and Sample* -A schematic diagram of the arrangement of the detection coils and the sample is shown in Fig. 1. Figure 2 indicates directions of the applied and sample fields.

The sample is rigidly mounted between the pole-pieces of an electromagnet, in such a way that its position relative to the detection coils is reproducible to ±0·08 mm in any direction. All parts of the sample holder shall be made of non-magnetic material.

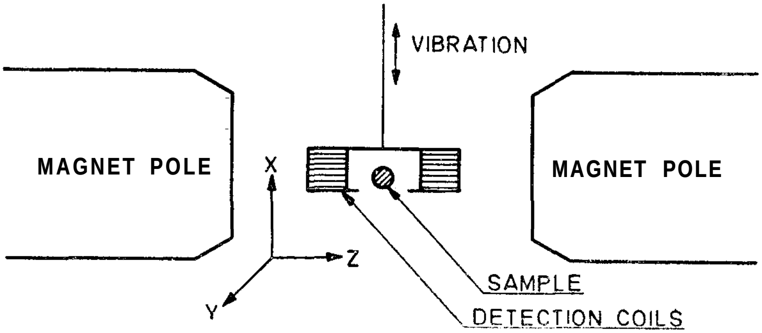

FIG. 1 VIBRATING COIL METHOD — SAMPLE AND COIL ARRANGEMENT

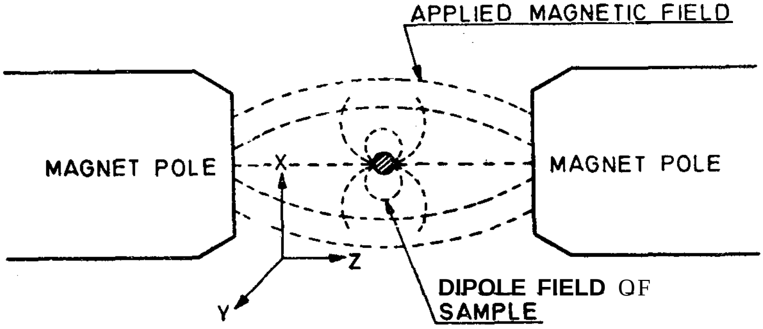

FIG. 2 MAGNETIC FIELD CONFIGURATION

The detection coils are an identical pair wound in series opposition. They are attached to the vibrator by a rigid, non-magnetic arm, and are located as close to the sample as practicable. Their axes are normally parallel to the direction of vibration, but other configurations are acceptable.

The direction of vibration (the X-direction) is at 90° to the x-axis of the electromagnet (Fig. 1), that *is,* perpendicular to the magnetostatic field direction, and the amplitude should be of the order of 0·05 to 0·5 mm. Frequency is not critical, but would normally be between 20 Hz and 200 Hz, although frequencies outside that range are acceptable. Motion of the coils in the Z- and Y-directions shall be limited by means of an appropriate mounting to more than 1 percent of that in the X-direction. Some means ofstabilizing the vibration amplitude by means of a feedback loop may be incorporated if required.

4.5.2 *Electromagnet* — The magnetostatic field should be capable of fully saturating a spherical specimen of the material to be measured. For most microwave ferrites, a field of 300 kAm^{-1} will be adequate. But for the hexagonal, barium-based ferrites up to 500 kAm^{-1} may be needed. The current supply to the electromagnet should be such as to maintain the field stable to 0·5 percent.

At the mean position of the detection coils, the radial field should be not more that 0·01 percent of the longitudinal field.

Since the uniformity of the field is dependent on the field-strength, measurements shall always be made at an applied field at which calibration and zero-setting have been carried out,

4.5.3 *Elimination of Applied Field Effects* — If the applied field were wholly uniform and had no radial components, when the direction of vibration was exactly at right angles to the applied field, the theory of 4.3 could be applied directly to the experimental arrangement of Fig. 1.

However, as indicated in Fig. 2, the applied field is not uniform, its direction and magnitude vary from point to point. Moreover, it is impractical to make an identical pair of detection coils. The angle of vibration will deviate from 90° and some residual motion in the Y- and <-directions will always be present.

Voltages will therefore be induced in the coils by the components H_x, H_y, H_z, of the applied field. The effect of H_z, is considerably lessened by winding the coils in opposition, so that voltages due to H_z tend to cancel out whereas those due to the sample dipole field will add up. However, complete cancellation cannot in general be achieved with one pair of coils alone. Therefore a second pair of coils, the compensating coils, are used. These are mounted on the same formers as the sample coils, but are wound in series, additionally relative to H_z. A compensating voltage may then be obtained, which may be adjusted in amplitude and phase to balance out the voltage induced in the sample coils by H_z.

The effect of H_x is more difficult to eliminate because the voltages induced in the sample coils will be added in the same way as those due to the dipole field. However, in general, the variation of H_x with x will be different from that of the sample dipole field. The latter will decrease as $1/X^2$, while H_x will tend to rise as the distance from the axis of the pole-pieces increases. The two signalswill therefore differ in phase and may be distinguished by means of a phase sensitive detector.

4.5.4 *Electronic Instrumentation* — A schematic diagram of the measuring apparatus is shown in Fig. 3. The vibrator is driven by a low frequency oscillator (9), which may be tunable, and a power amplifier. The amplitude of the oscillator output and the gain of the power amplifier should be sufficiently stable to provide a constant drive to the vibrator to within ±0·3 percent, after warm-up. If this is not possible, some means of stabilizing the vibration amplitude shall be provided. The oscillator frequency should be stable to 0·05 percent after warm-up.

The output from the compensating coils, 1 (c), is balanced against that of the sample coils 1 (s), by means of the difference amplifier (4), using the variable attenuator (2) and phase shifter (3). The phase shifter should be fully variable over 360” and its resolution should be at least ±0·1°. Neither the phase shifter nor the attenuator needs to be calibrated.

The difference amplifier should have a low enough noise level at low frequencies to allow precise zero setting. The exact requirements will depend on the design of the coils and other equipment. A variable gain control may be incorporated.

The low pass filter (5), should reduce all harmonics by at least *20* dB with respect to the fundamental frequency.

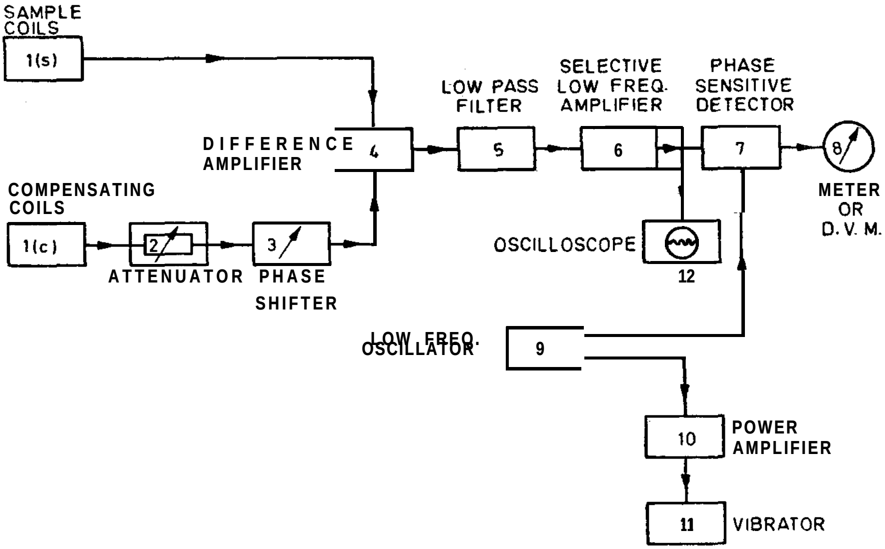

FIG. 3 MEASURING APPARATUS FOR VIBRATING COIL METHOD

The selective amplifier, which is tuned to the oscillator frequency, should have a bandwidth of the order of 1 percent and should be tunable if the oscillator is not tunable.

The phase sensitive detector (7) should have a resolution better than 3” and either the reference or signal channel should be variable over 360” in phase. The phase setting shall be independent of the amplitude of the input to either channel.

The meter (8) may be an analogue or digital type. When measurements are to be made over a range of temperatures, an X-Y-recorder may be substituted for the meter, one axis to record a linear function of magnetization, the other a linear function of temperature. Roth axes shall be calibrated to the accuracy required. The temperature measuring device, normally a thermocouple, shall be in close thermal contact with the sample itself.

All electronic instruments shall have adequate temperature stability to ensure the required accuracy over the range of ambient temperatures to be met in use.

4.6 Measuring Apparatus for the Vibrating Sample Method (VSM)

4.6.1 *Arrangement of Detection Coils and Sample-* In this case, the detection coils (Fig. 4) are rigidly mounted between the pole-pieces of the electromagnet, but in such a way that frequent small adjustments are

possible. Normally their axes are at right angles to the applied field and parallel to the direction of vibration, but other configurations are acceptable. The mean sample position is on the axis of the electromagnet, normally located symmetrically with respect to the detection coils. Its position should be reproducible to ±0·08 mm. It is rigidly mounted on a non-magnetic vibrating arm, attached to a vibrator, and is as close to the detection coils as practicable.

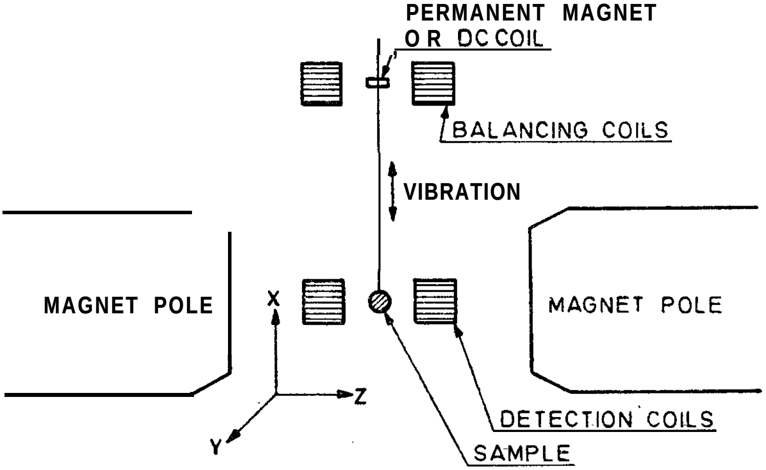

FIG. 4 VIBRATING SAMPLE METHOD-SAMPLE AND COIL ARRANGEMENT

The direction of vibration (the X-direction) is at 90” to the <-axis of the electromagnet (Fig. 4), that is perpendicular to the magnetostatic field direction, and the amplitude should be of the order of 0·05 to 0·5 mm. Frequency is not critical, but would normally be between 20 Hz and 200 Hz, although frequencies outside that range are acceptable. Motion of the sample in the *Z*- and *Y*-directions should be limited by means of a suitable mounting to not more than 5 percent of that in the X-direction. Some means of stabilizing the vibration amplitude by means of a feedback loop may be incorporated if necessary.

A small permanent magnet is attached to the vibrating arm, far enough away from the electromagnet to be unaffected by it. Two small coils are mounted rigidly on either side of this magnet to detect its field. A small coil carrying a precisely controlled direct current may be used instead of the magnet.

4.6.2 *Electromagnet-No* precautions need be taken to counteract curvature and non-uniformity of applied field, provided that a uniformity of about **3** percent over the volume of the sample is maintained. A radial field of up to 1 percent of the longitudinal field is permissible.

The magnetostatic field should be capable of fully saturating a spherical specimen of the material to be measured. For most microwave ferrites, a field of 300 kAm^{-1} will be adequate, but for the hexagonal, barium-based ferrites up to 500 kAm^{-1} may be needed. The current supply should maintain the field stable to about 0·5 percent.

4.6.3 *Electronic Instrumentation* — A schematic diagram of the electronic instrumentation is shown in Fig. 5. The simplest arrangement uses only items 1 to 8, and allows point-by-point measurements to be made at fixed temperatures. The calibrated potential divider (3) is used to balance the voltage induced in the balancing coils against that in the sample coils. The null point is observed by means of the oscilloscope (5). Magnetization is calculated from the potential divider setting.

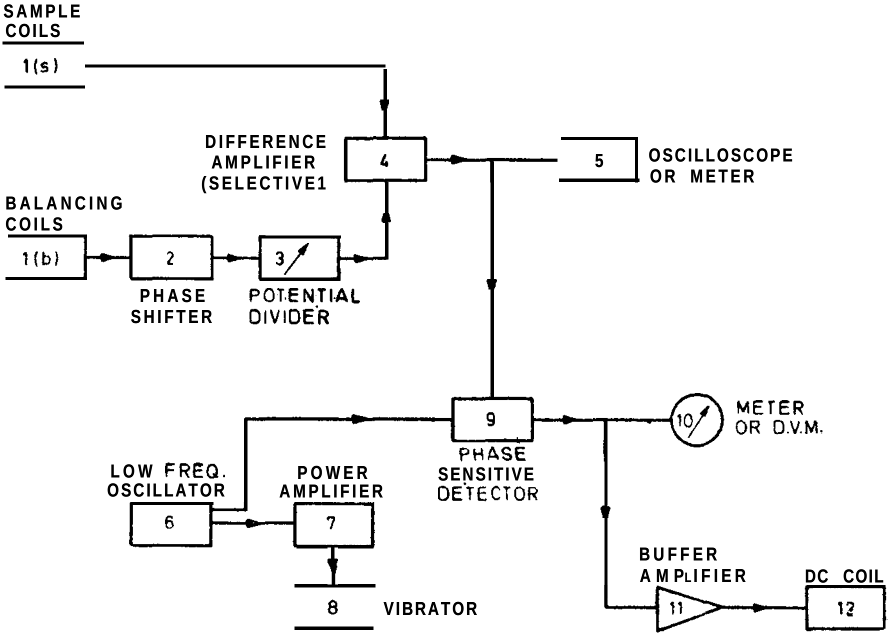

FIG. 5 MEASURING APPARATUS FOR VARIABLE SAMPLE METHOD

Alternatively, the null balance may be made with the empty sample holder in position. The out-of-balance signal on insertion of a sample is then proportional to magnetization. This signal may be read directly from the meter (5) or oscilloscope. For continuous plotting of M_s as a function of temperature, an X-Y-recorder may be substituted for the oscilloscope, Greater sensitivity and better stability may be obtained by use of a phase sensitive detector (9) to detect the signal, which may then be observed by means of a meter or recorder.

If a dc coil (12) is used instead of a permanent magnet to obtain the balancing voltage, automatic null balancing may be achieved by feeding the output of this phase sensitive detector to the dc coil. The current in the coil is then directly proportional to magnetization.

The vibrator is driven by a low frequency oscillator, which may be tunable, and a power amplifier. The amplitude of the oscillator output and the gain of the power amplifier should be sufficiently stable to maintain the drive to the vibrator at a constant level, to within 0·3 percent after warm-up. If this is not possible, some means of stabilizing the vibration amplitude must be provided. The oscillator frequency should be stable to 0·05 percent after warm-up.

The potential divider should be continuously variable, with a resolution of 0·01 percent or better and shall be calibrated to the accuracy required.

The difference amplifier should have a sufficiently low noise level and should incorporate, or be followed by, a selective amplifier with a bandwidth of the order of 3 percent tuned to the oscillator frequency. The selective stage must be tunable if the oscillator is not tunable.

The requirements for the phase sensitive detector are not stringent. A resolution of 10” is adequate. The phase setting must be independent of the amplitude of the input to either channel.

The meters may be analogue or digital types. When measurements are to be made over a range of temperatures, an X-Y-recorder may be substituted for the meter, one axis to be a linear function of magnetization, the other a linear function of temperature. Both shall be calibrated to the accuracy required. The temperature measuring device, normally a thermocouple, shall be in close thermal contact with the sample itself.

All electronic equipment shall have adequate temperature stability to maintain the required accuracy over the range of ambient temperatures to be met in use.

4.7 **Calibration -The** following calibration methods are equally applicable to either the vibrating coil or the vibrating sample methods.

4.7.1 *Comparison Method-This* method calls for a standard sample, whose saturation magnetization is accurately known. The most usual material for the standard, is pure nickel, but other materials may be used if their saturation magnetization is known accurately enough.

The calibration sample shall be a sphere (if the samples to be measured are spheres) and should be of similar order of size. (If samples other than spheres have to measured, calibration samples with identical dimensions shall be used.) The calibration sphere should show a deviation from roundness of not more than 0·25 percent and its mean diameter shall be known to within 0·1 percent Metallic standard spheres should be fully annealed before use.

The density of the material to be used as a standard shall first be determined. The generally accepted value for the saturation magnetization of 99.995 percent pure nickel with a density of 8·90 g.cm^{-3}, is 485.6 kAm^{-1} at 23°C. For less dense material,

$$M_s = \frac{485{\cdot}6 \times \text{density}}{8{\cdot}90} \ (kAm^{-1}) \qquad \dots (7)$$

However, the actual value for a specific sample may differ from this by as much as 1 percent, depending on purity, state of strain, applied field, or ambient temperature. The accuracy of the comparison method is therefore limited.

4.7.2 *'Slope' Method* — This method is based on the observation that the voltage induced in the detection coils by a spherical specimen *is* directly proportional to the applied field over the lower region of the magnetization curve. Furthermore, the constant of proportionality is independent of the permeability, provided that the latter is sufficiently high.

From equation (2) the voltmeter reading for the calibration sample is

$$E_c = KM_c\, d_c^3 \qquad \dots (8)$$

$$\triangle E_c = Kd_c^3 \triangle M_c \qquad \dots (9)$$

where K is a constant.

Similarly, for an unknown sample the reading is

$$E_s = KM_s d_s^3 \qquad \dots (10)$$

$$A\ \&\ = Kd_s^3\ AM, \qquad \dots (11)$$

If a graph is plotted, for the calibration sphere, of E_c against applied field H_o, in the region well below saturation, then

$$M_c = (\mu_r - 1)\ H\,i \qquad \dots (12)$$

where μ is the permeability of the calibration sphere; and H_i is the internal field in the sphere, given by:

$$H_i = H_o - NM_c \qquad \dots (13)$$

where the demagnetizing factor, $N = 1/3$ for a perfect sphere.

The slope of this graph is AE_c/AH_o.

Combining equations (12) and (13)

$$M_C = \frac{H_o}{\dfrac{1}{(\mu_r - 1)} + \mathcal{N}} \qquad \dots (14)$$

Therefore $\Delta M_c = \dfrac{\Delta H_o}{\dfrac{1}{(\mu_r - 1)} + \mathcal{N}}$ $\qquad \dots (15)$

From equations (9) and (14)

$$\frac{\Delta E_c}{K d_c^3} = \frac{\Delta H_o}{\dfrac{1}{(\mu_r - 1)} + \mathcal{N}}$$

$$K = \frac{\{(\mu_r - 1)^{-1} + \mathcal{N}\}}{d_c^3} \cdot \frac{\Delta E_c}{\Delta H_o} \qquad \dots (16)$$

From equations (10) and (16):

$$M_s = \frac{E_s d_c^3}{\{(\mu_r - 1)^{-1} + \mathcal{N}\} d_s^3 \cdot \dfrac{\Delta E_c}{\Delta H_o}} \qquad \dots (17)$$

If μ_r = 2 000, the error for M_s in assuming $(\mu_r - 1)^{-1}$ negligible compared to $\mathcal{N}$ = 1/3 is only + 0·15 percent.

A deviation from roundness of 0·25 percent leads to a maximum error in $\mathcal{N}$ of 0·25 percent.

Therefore, to within 0·4 percent

$$M_s = \frac{3 E_s d_c^3}{d_s^3 (\Delta E_c / \Delta H_o)} \qquad \dots (18)$$

A pure (99.995 percent) iron sphere is a suitable calibration standard.

4.8 Measuring Procedure

4.8.1 *Zero Setting for Vibrating Coil Method* -The electromagnet current is switched on, with the empty sample holder between the poles. The detection coils are allowed to vibrate. The attenuator and phase shifter are adjusted to obtain a minimum output from the selective amplifier, as observed on the oscilloscope.

The applied field is then altered and the attenuator and phase shifter settings checked. If these have changed singnificantly, the location of the coils is adjusted and the zero re-set, until a position is found at which the zero setting is sufficiently independent of applied field over the range of interest.

,A calibration sample is placed in the holder and the phase sensitive detector adjusted until a maximum reading obtained on the voltmeter.

4.8.2 *Zero Setting for Vibrating Sample Method*- The balancing coils are first made as insensitive as possible to the exact position of the reference magnet (or dc coil). In the absence of any signal from the detection coils, the balancing coils are rotated about the X-axis for maximum output. They are then adjusted in the <-direction for minimum output, in the Y-direction for maximum output and in the X-direction for a maximum (if the coils are short) or minimum (if they are long). The output is now independent of small changes in the position of the magnet.

The balancing coils should now be firmly fixed in position and the above adjustments will not normally be repeated.

A sample is placed in the holder and similar adjustments carried out for the sample coil, in absence of a signal from the balancing coils.

4.8.3 *Taking the Measurement*-All electronic equipment should be switched on at least 30 minutes before starting measurements, to allow it to stabilize at the ambient temperature. The zero reading is checked with the sample holder empty and the apparatus adjusted if necessary.

A calibration sample is placed in the holder and the reading checked to ensure that it is correct for that particular specimen at the ambient temperature.

The diameter of the spherical sample is measured, making at least five separate micrometer or microscope measurements. The deviation from roundness is calculated according to equation (6).

The sample is fixed in the sample holder and the applied field set to the required value.

In the VSM case the potential divider setting is adjusted to obtain a null reading on the oscilloscope or, alternatively, if the null has been obtained for the empty sample holder, the meter reading is noted. If automatic null balancing with a dc coil is being used, the coil current is observed.

In the VCM case, the meter reading is noted.

The temperature of the sample is also observed. If measurements are to be made over a range of temperatures, the temperature is set to the lowest to be recorded, allowing enough time for the environmental chamber to stabilize, and then raised at not more than 3°C/min until the whole temperature range of interest has been covered.

4.9 Calculation — The readings are converted into values of magnetization, using either equation (5) or (18) according to whether the calibration method was as described in 4.7.1 or 4.7.2.

4.10 Accuracy — The accuracy of either the VCM or VSM will depend on the method of calibration. If the comparison method is used, a systematic error of up to 1 percent may be introduced because of uncertainty in the magnetization of the calibration sample. The slope method is somewhat better because the absolute value of M_c is not needed. In that case the error due to uncertainty in the calibration may be kept less than 0·5 percent.

The relative error for the VCM is typically ± 3 percent, and that for the VSM is typically ±1·5 percent.

These relative errors will of course depend on the value of M_s, being greater for low values of saturation magnetization.

4.11 **Data Presentation** — Values of M_s obtained by either method should be quoted as follows:

> Saturation magnetization at a temperature of 0°C = XYZ kAm^{-1} ± estimated error.

Where M_s has been plotted as a function of temperature, the actual curve should be given together with an estimate of accuracy of both M_s and temperature measurements.

SECTION 2 METHOD FOR MEASUREMENT OF MAGNETIZATION (AT SPECIFIED FIELD STRENGTH) M_H

5. SCOPE

5.1 This section describes method for measurement of magnetization (at specified field strength) M_H.

6. METHOD OF MEASUREMENT

6.1 Introduction — For theoretical computations of tensor permeability components, knowledge of the saturation magnetization of the material is necessary [see IS : 1885 (Part XII)-1966*]. However, in general, the ferrite material in a microwave component is not completely saturated.

For example in the recently developed so-called latching devices, the ferrite is in a state of remanence. Therefore, a method has been sought whereby more general information on the hysteresis loop properties of a material may be obtained. The applicability of this method is somewhat limited by the fact that the test specimen has to be a toroid or, at least a closed magnetic circuit that may, with sufficient accuracy be expressed in terms of an equivalent toroid.

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*Electrotechnical vocabulary: Part XII Ferromagnetic oxide materials.

6.2 Object - The measuring method described in this section has been developed primarily in order to measure magnetization. However, it also permits simultaneous measurement of a number of other magnetic properties, for instance remanent magnetization and coercive field strength when the material is in cyclic magnetic condition. The 'squareness ratio' of the material may be calculated, and the hysteresis loop may be continuously displayed on an oscilloscope during measurements. The latter fact enables one to check qualitatively the sensitivity of the material to mechanical stress.

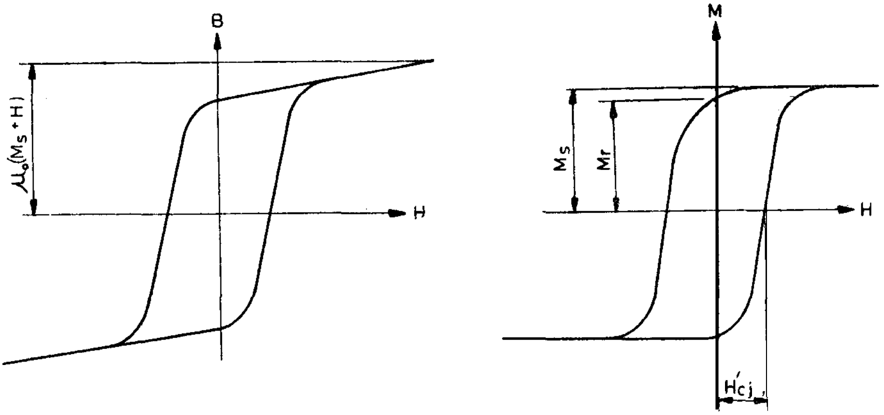
By placing the test specimen in a programmed temperature test chamber all quantities may be obtained as functions of temperature. By allowing for a sufficient temperature sweep range, Curie temperature and, for certain materials, compensation temperature may be determined.

6.3 **Theory** - In a ferrite toroid the following relation between flux density B, magnetization M, and field strength H, is valid:

$$B = \mu (H + M) \qquad \ldots(19)$$

If the ratio of outer to inner diameter of the toroid is close to unity, all the field quantities may be assumed to be reasonably constant over the toroid cross section.

If H is varied periodically and symmetrically and B is measured simultaneously and plotted as a function of H in a Cartesian coordinate system a dynamic BH-loop is obtained (Fig. 6A). This curve may be changed into an MH-loop by subtracting from B a quantity equal to $\mu_0 H$ (Fig. 6B). If the variation in H is sufficiently large the height of the curve becomes independent of any further increase in H, and equal to $\mu_0 M_s$ where M_s is the saturation magnetization. In this case, the intercepts of the loop with the H-axis correspond to the cyclic coercivity, H'_{cj}.



A — BH-Curve *B* — *MH*-Curve

FIG. 6 HYSTERESIS CURVES FOR A MAGNETIC MATERIAL

If a winding consisting of N_1 turns is uniformly distributed over a toroidal core having rectangular cross section, a current I, through that winding gives rise to a magnetic field inside the core with a mean value equal to:

$$H = \frac{N_1 I}{2\pi r_m} \qquad \dots (20)$$

where r_m is the mean radius of the core calculated as:

$$r_m = \frac{\ln r_2 - \ln r_1}{\dfrac{1}{r_1} - \dfrac{1}{r_2}} \qquad \dots (21)$$

where r_1 and r_2 are the inner and outer radii of the toroid, respectively (see IS: 7616-1974*).

If a secondary winding of N_2 turns is uniformly distributed over the same core, an electromotive force E, proportional to the time derivative of the flux density in the core is induced in that winding:

$$E = k \cdot \frac{dB}{dt} \qquad \dots (22)$$

where $k = N_2 A_e$ and A_e equals the effective cross section of the specimen as defined in 6.3.

Had the same two windings been placed on a non-magnetic core the induced voltage would have been proportional to the time derivative of the field strength:

$$E' = k.\ \mu_0 \cdot \frac{dH}{dt} \qquad \dots (23)$$

The arrangements described above correspond to a ferrite-core and an air-core transformer, respectively. If two such transformers, one of either kind, are connected in series opposition as shown in Fig. 7 the total output voltage U is equal to:

$$U = E - E' = k\left(\frac{dB}{dt} - \mu_0 \frac{dH}{dt}\right) \qquad \dots (24)$$

whence

$$U = k.\ \mu_0 \cdot \frac{dM}{dt} \qquad \dots (25)$$

By integrating the voltage, another voltage proportional to M may be obtained. Thus, keeping in mind that H is proportional to I we have at our disposal two electric quantities that may be used to give an analog representation of the *MH-loop.*

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*Guide for calculation of the effective parameters of magnetic piece parts.

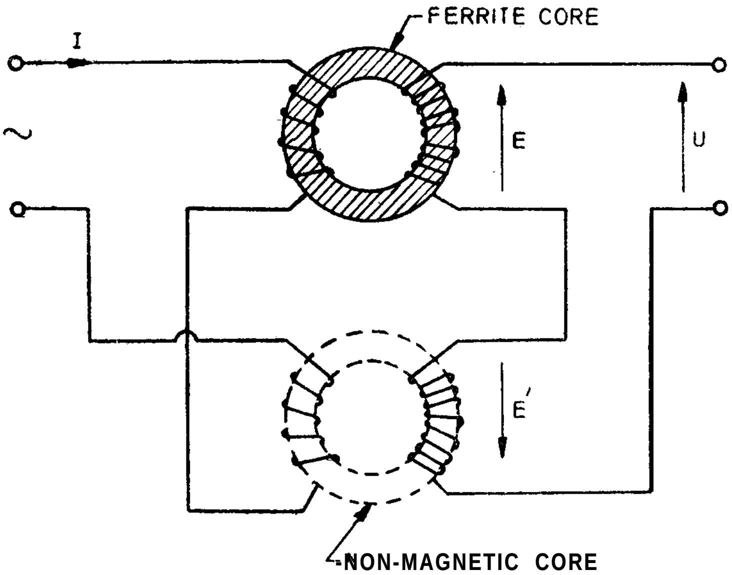
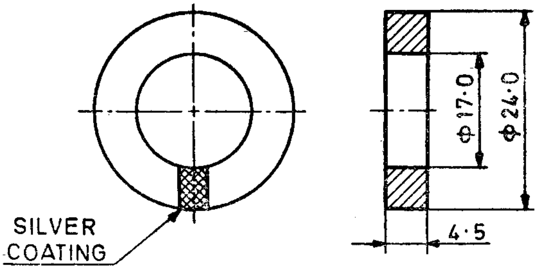


FIG. 7 TEST SAMPLE WITH COMPENSATION UNIT

6.4 **Test Specimen** -A toroid is made from the material to be investigated. An example of suitable dimensions of the toroid is given in Fig. 8, but other dimensions may be used, provided that the ratio of inner to outer diameter exceeds 0·7.



All dimensions in millimetres.

FIG. 8 TEST SPECIMEN

A minor portion of one of the flat sides of the specimen is silver-coated. A suitable silver preparation should after curing show good adhesion and solderability.

A high-melting solder (melting point approximately 310°C) is prepared by making an alloy of about 90 percent (by mass) of lead and the remainder tin. This alloy, which may be used in the same way as

-ordinary solder is used to fix a thermocouple (copper-constantan) on to the silver-coated portion of the core surface. This thermocouple measures the real core temperature with reasonable accuracy. Some sort of protective coating may be applied to the thermocouple junction to minimize direct heat radiation pick up.

Heating (such as during silver curing or soldering) may be harmful to certain ferrite-materials. If this is the case, other means for assuring good thermal contact with the thermocouple should be considered.

The next step is to place two windings on the core, first the search coil, consisting of a single layer containing 200 turns of 0·2 mm copper wire with a heat-resistant lacquer such as polyamide. The winding should be spread as evenly as possible over the core excluding only the silver-coated part. Secondly, the drive coil is wound on top of the search coil. The drive coil consists of 70 turns of 0·5 mm copper wire with heat-resistant lacquer. The figures given above should be taken as examples only, other numbers of turns may equally well be used, provided that it is taken into account in the calculations.

6.5 **Measuring Apparatus** — The test specimen and a similar transformer (compensation unit), wound on a non-magnetic core of the same dimensions as the ferrite toroid are connected to a measuring circuit as shown in Fig. 9. A power source delivering a 0 to 5 V, 50 — 60 Hz sinusoidal voltage

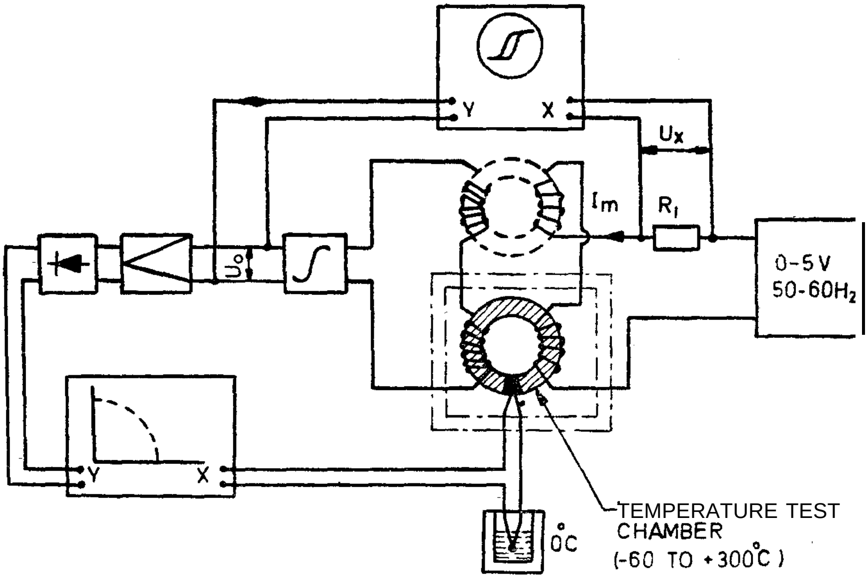


FIG. 9 MEASURING CIRCUIT

is connected to the primary windings through a resistor R_i. The resistor is made of a short length of constantan wire and has, in the example given here, a resistance of 0.096 3 ohm. (If care is exercised, the resistance may be increased somewhat, to allow for a lower sensitivity of the oscilloscope X input.) The voltage drop across the resistor U_x is fed to the horizontal input of an oscilloscope.

This voltage is proportional to the drive current I_m and hence to the magnetic field strength H_m. It follows that:

$$U_x = I_m \cdot R_i = \frac{H_m \, l_m}{N_1} R_i \qquad \ldots (26)$$

where l_m is the mean flux path length and N_1 is the number of primary turns. An input signal of 1 V corresponds to a field strength equal to:

$$H_m = \frac{N_1}{1\mathrm{m} \cdot R_i} \qquad \ldots (27)$$

or, with the figures used in this example inserted, 1 $1{\cdot}51{\cdot}10^3 \, A_m^{-1}$. Therefore, an oscilloscope input voltage of 1 mV corresponds to a field strength of $11{\cdot}51 \, A_m^{-1}$.

The output voltage from the two secondary windings connected in series is proportional to the time derivative of M. To obtain a signal proportional to M it has to be integrated, which is done in a Miller integrator.

A Miller integrator can be built with the aid of an operational amplifier according to Fig. 10.

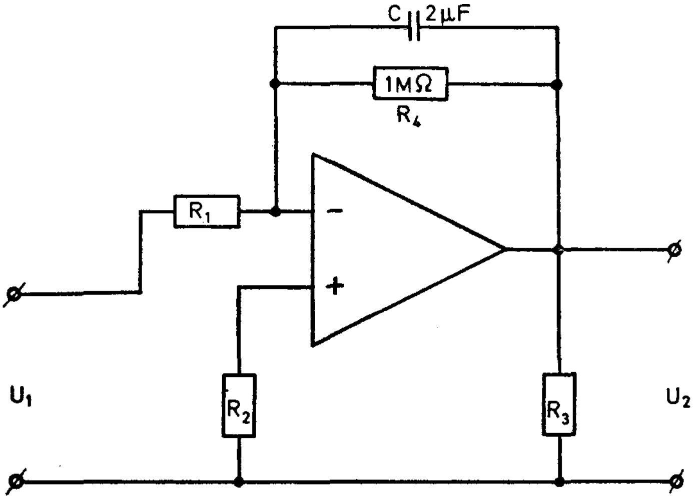


FIG. 10 MILLER INTEGRATOR

In order to have satisfactory performance from the integrator, its effective time constant K.C.G., (where G is the amplifier gain) should exceed the reciprocal of the measuring frequency by a factor of at least 100.

The integrator output voltage is equal to:

$$U_2 = \frac{\mu_0 M N_2 A_e}{RC} \cdot \frac{G}{G+1} \qquad \dots (28)$$

where

$$A_e = \frac{h \ln^2 \frac{r_2}{r_1}}{\frac{1}{r_1} - \frac{1}{r_2}} \qquad \dots (29)$$

is the effective cross section area of the core and N_2 is the number of secondary turns.

This signal U_2 is fed to the vertical input of the oscilloscope. Typically, an input voltage of 1 mV corresponds to an M_H value of approximately 2 kA/m.

It should be borne in mind that bandwidth and sensitivity of the oscilloscope should be adequate. A low frequency limit of less than 0·25 Hz (preferably dc) and an upper limit of more than 10 kHz will give satisfactory results. The sensitivity of the X and Y amplifiers should exceed 2 mV^{-1}.

The oscilloscope Y input signal is also amplified to a level of 10 to 20 V and subsequently rectified in a peak-sensing rectifier. The rectified signal is fed to the Y input of an X-Y-recorder. The X input of the recorder is fed by the thermocouples in such a way that the recorder deflection is directly proportional to the core temperature in °C. Thus a diagram showing the temperature dependence of M_H is obtained.

6.6 Calibration — The oscilloscope inputs are calibrated with the aid of an external, high precision voltage source. The recorder is adjusted to correct sensitivity with regard to the temperature interval and the expected maximum value of M_H in that region.

The output from the power source -is adjusted (with the aid of the oscilloscope) so that the field strength amplitude is equal to $n \times H'_{cj}$ (where n is an integer, usually 5) at room temperature. This value (for example the width of the oscilloscope display) should be kept constant during the entire measurement.

6.7 Measuring Procedure — All electronic equipment should beswitched on approximately 30 minutes before measurement, to ensure adequate stability. The test specimen is mounted in the temperature test chamber and its windings and thermocouple leads are connected to the measuring circuit. The X- and Y- amplifiers of the oscilloscope are calibrated.

The drive current is increased so that the maximum magnetic field strength is equal to the desired value, usually five times the coercive field strength. The sensitivity of the X-Y-recorder is adjusted and its Y-axis calibrated against the value of M read off the oscilloscope screen.

The temperature of the test chamber is brought down to the lowest temperature of interest. The measurement starts from this point and the temperature is allowed to rise so slowly (typically less than 3°C/min) that the test specimen may be considered to be in reasonable thermal equilibrium. The maximum value of M (M_H) is automatically recorded as a function of temperature. At certain temperatures, readings of remanent magnetization and coercive field strength are taken. Alternatively, photos may be taken for more detailed study of loop configuration.

The measurement is terminated when the temperature has reached an appropriate value-; normally a temperature a little above the Curie point is chosen.

6.8 **Calculation** — The oscilloscope readings, whether obtained from direct observation or photos, are converted into values of magnetization and field strength using the expressions given in 6.5. The ratio, $M_r/(\hat{M}+\hat{H})$, is calculated using values thus obtained. The recorder curve is self-explanatory and requires no further calculation.

6.9 **Accuracy** — The measuring accuracy will vary with M_H, the error generally increasing when a transition temperature is approached and M_H becomes small. Sufficiently far from these points the systematic error is, however, very small, of the order of $+$ 1 percent, provided that the measuring circuit is correctly built. On top of this should be put the uncertainty introduced by the read-out instrumentation. This quantity may be very difficult to establish.

The following relative errors are typical of data obtained according to this method.

$M_H = \pm$ 3 percent (*Max*)

$H'_{cj} = \pm$ 5 pereent

Curie point = 2°C

Squareness ratio = ± 6 percent

6.19 **Data Presentation-** Values of M_H obtained by this method should be quoted as follows:

a) Magnetization at a magnetic field strength equal to n times the coercive field strength and at a temperature of θ°C $- XYZ$ kAm^{-1} ± 3 percent or, in the case of remanent magnetization.

b) Remanent magnetization when the magnetic field strength has been decreased from n times the coercive field strength to zero at a temperature of θ°C — XYZ kAm^{-1} ± 3 percent.

In cases where M_H is plotted against temperature., the actual curve should be given together with a statement concerning the estimated accuracy.

APPENDIX A

(Clause 0.4)

IS : 8426	Method of measurements for properties of gyromagnetic materials for use at microwave frequencies:
Part I	Magnetization, Section 1 Saturation magnetization, M_s Section 2 Magnetization (at specified field strength) M_H
Part II	Resonance linewidth Section 1 Gyromagnetic resonance linewidth, ΔH and effective landé factor, g_{eff} (general) Section 2 Spin-wave resonance linewidth, ΔH_k Section 3 Effective resonance linewidth, ΔH_{eff}
Part III	Permittivity, apparent density and Curie temperature Section 1 Complex permittivity, ε_r Section 2 Apparent density, ρ_{app} Section 3 Curie temperature, θc

INDIAN STANDARDS
ON
MAGNETIC COMPONENTS AND FERRITE MATERIALS

IS :	
1176-1969	Dimensions for aerial rods and slabs made of ferromagnetic materials
1885	Electrotechnical vocabulary.
(Part XII)-1966	Part XII Ferromagnetic oxide materials
(Part XXXI)-1971	Part XXXI Magnetism
(Part XXXXI)-1975	Part XXXXI Non-reciprocal electromagnetic components
2032 (Part XVII)-1975	Graphical symbols used in electrotechnology: Part XVII Symbols for ferrite cores and magnetic storage matrices
6077 (Part I)-1971	Permanent magnets: Part I General requirements and tests
6235-1971	Dimensions of pot-cores made of ferromagnetic oxides and associated parts
7416	Dimensions for TV ferrite components
(Part I)-1974	Part I Cores for deflection coil
(Part II)-1976	Part II Ferrite rod for linearity control unit
(Part III)-1976	Part III Tuning magnet for linearity control unit
(Part IV)-1976	Part IV Ring magnet for linearity control unit
(Part V)-1976	Part V Segment magnet for linearity control unit
(Part VI)-1976	Part VI Beam centering magnet for deflection coil
(Part VII)-1976	Part VII Pin cushion correction magnet for deflection coil
(Part VIII)-1976	Part VIII U and I Core assembly for line output transformer
(Part X)-1976	Part X Corner correction magnet
(Part XI)-1976	Part XI Balun corner
7430-1974	Dimensions of screw cores made of ferromagnetic oxides
7431 (Part I)-1974	Tests for magnetic properties of ferrite aerial rods : Part I For long and medium wave receptions
7431 (Part II)-1976	Tests for magnetic properties of ferrite aerial rods: Part II For short wave reception
7489-1974	Dimensions of cross cores (X-cores) made of ferromagnetic oxides and associated parts
7527-1974	Dimensions of loudspeaker magnets
7616-1974	Guide for calculation of the effective parameters of magnetic piece parts
7687-1974	Methods of measurement for cores for inductors and transformers for telecommunications
7717-1974	General requirements and tests for magnetic cores for application in coincident current matrix stores having a nominal selection ratio of 2 : 1 and in linear select memory stores
7930-1976	Dimensions of toroids made of magnetic oxides or iron powder
7934-1976	Dimensions of square cores made of magnetic oxides and associated parts
8426 (Part I)-1977	Methods of measurements for properties of gyromagnetic materials for use at microwave frequencies : Part I Magnetization

INTERNATIONAL SYSTEM OF UNITS (SI UNITS)

Base Units

Quantity	*Unit*	*Symbol*
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Luminous intensity	candela	cd
Amount of substance	mole	mol

Supplementary Units

Quantity	*Unit*	*Symbol*
Plane angle	radian	rad
Solid angle	steradian	sr

Derived Units

Quantity	*Unit*	*Symbol*	*Conversion*
Force	newton	N	1 N = 1 kg.1 m/s^2
Energy	joule	J	1 J = 1 N.m
Power	watt	W	1 W = 1 J/s
Flux	weber	Wb	1 Wb = 1 V.s
Flux density	tesla	T	1 T = 1 Wb/m^2
Frequency	hertz	HZ	1 Hz = 1 c/s (s-1)
Electric conductance	siemens	S	1 S = 1 A/V
Pressure, stress	pascal	Pa	1 Pa = 1 N/m^2